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[45] **Date of Patent: Sep. 15, 1998**

[54] **THIN FILM RESONANT MICROBEAM ABSOLUTE PRESSURE SENSOR**

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[73] Assignee: **Honeywell Inc.**, Minneapolis, Minn.

[21] Appl. No.: **777,651**

[22] Filed: **Dec. 31, 1996**

[51] **Int. Cl.**^{6} **G01C 11/00**

[52] **U.S. Cl.** **73/862.59**; 73/704

[58] **Field of Search** 73/702, 704, 715, 73/754, 862.59, 778

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,673,777	6/1987	Bai et al. .	
4,744,863	5/1988	Guckel et al. .	
4,841,775	6/1989	Ikeda et al.	73/704
4,873,871	10/1989	Bai et al. .	
5,009,108	4/1991	Harada et al.	73/704
5,060,526	10/1991	Barth et al.	73/702 X
5,105,665	4/1992	Parsons et al.	73/704
5,142,912	9/1992	Frische	73/702
5,146,787	9/1992	Thomas et al.	73/704
5,305,643	4/1994	Thomas et al.	73/704
5,417,115	5/1995	Burns .	
5,458,000	10/1995	Burns et al. .	
5,473,944	12/1995	Kurtz et al.	73/704
5,511,427	4/1996	Burns .	
5,550,516	8/1996	Burns et al. .	
5,559,358	9/1996	Burns et al. .	

FOREIGN PATENT DOCUMENTS

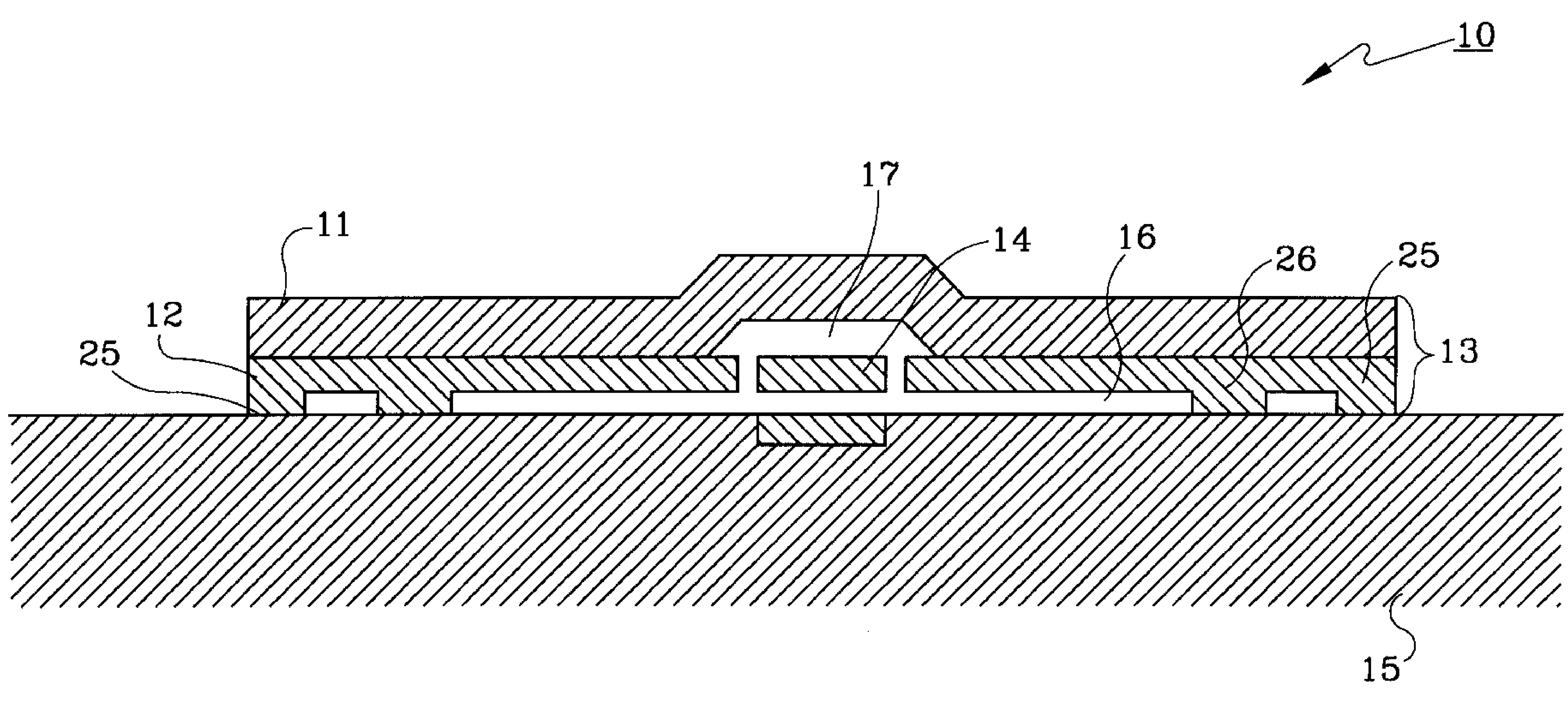
0083067A	7/1983	European Pat. Off. .
0266974A	5/1988	European Pat. Off. .
9428452A	12/1994	WIPO .

Primary Examiner—Ronald L. Biegel
Attorney, Agent, or Firm—John G. Shudy, Jr.

[57] **ABSTRACT**

A micromechnical sensor having a polysilicon beam that is an integral part of the diaphragm resulting in a frequency of the beam that is a direct result of the pressure applied to the external surface of the diaphragm. Fabrication of this resonant microbeam sensor has no backside wafer processing, and involves a process and layout independent of wafer thickness for high yield and robustness. Both the diaphragm and resonant beam are formed from polysilicon. The sensor may have more than one resonant beam. The sensor beam or beams may be driven and sensed by electrical or optical mechanisms. For stress isolation, the sensor may be situated on a cantilevered single crystal silicon paddle. The sensor may be recessed on the isolating die for non-interfering interfacing with optical or electrical devices. The sensor die may be circular for ease in mounting with fiber optic components.

7 Claims, 10 Drawing Sheets



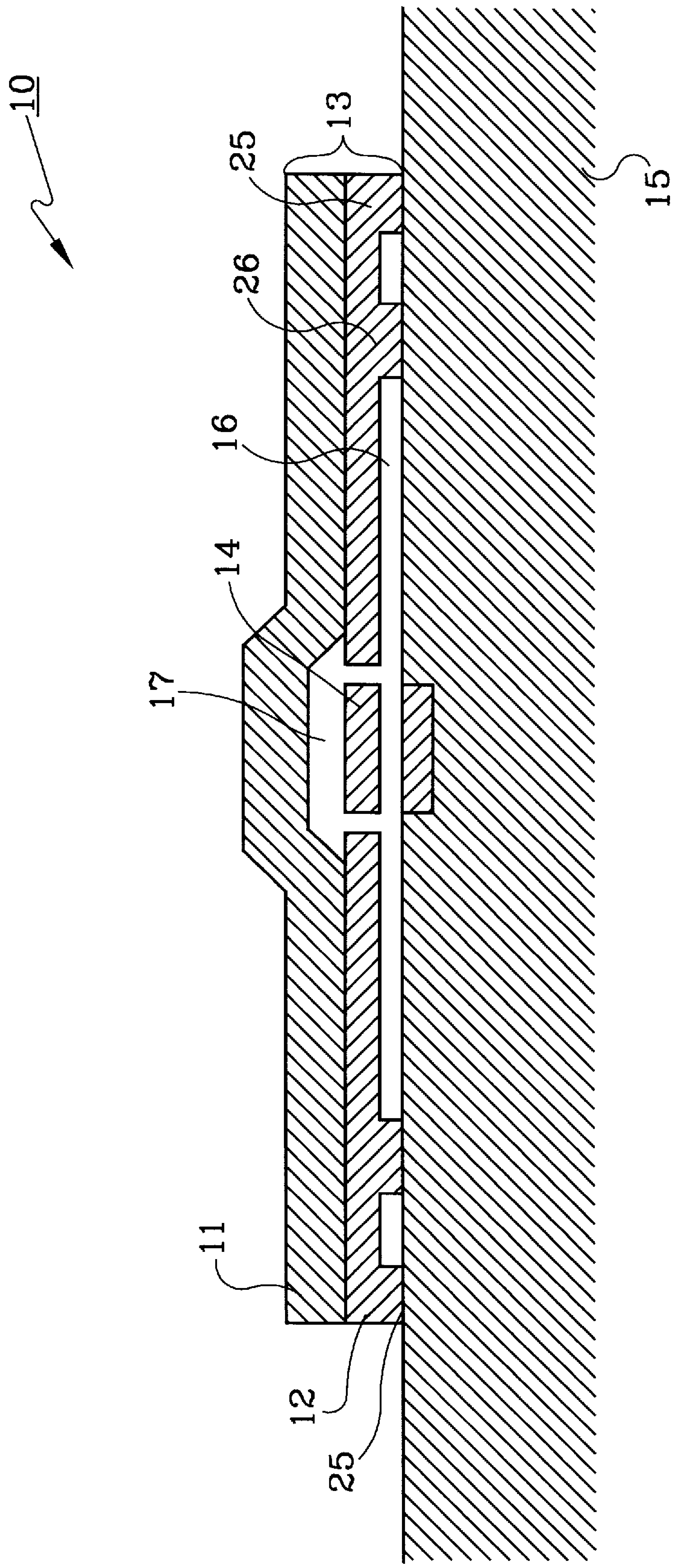


Fig. 1

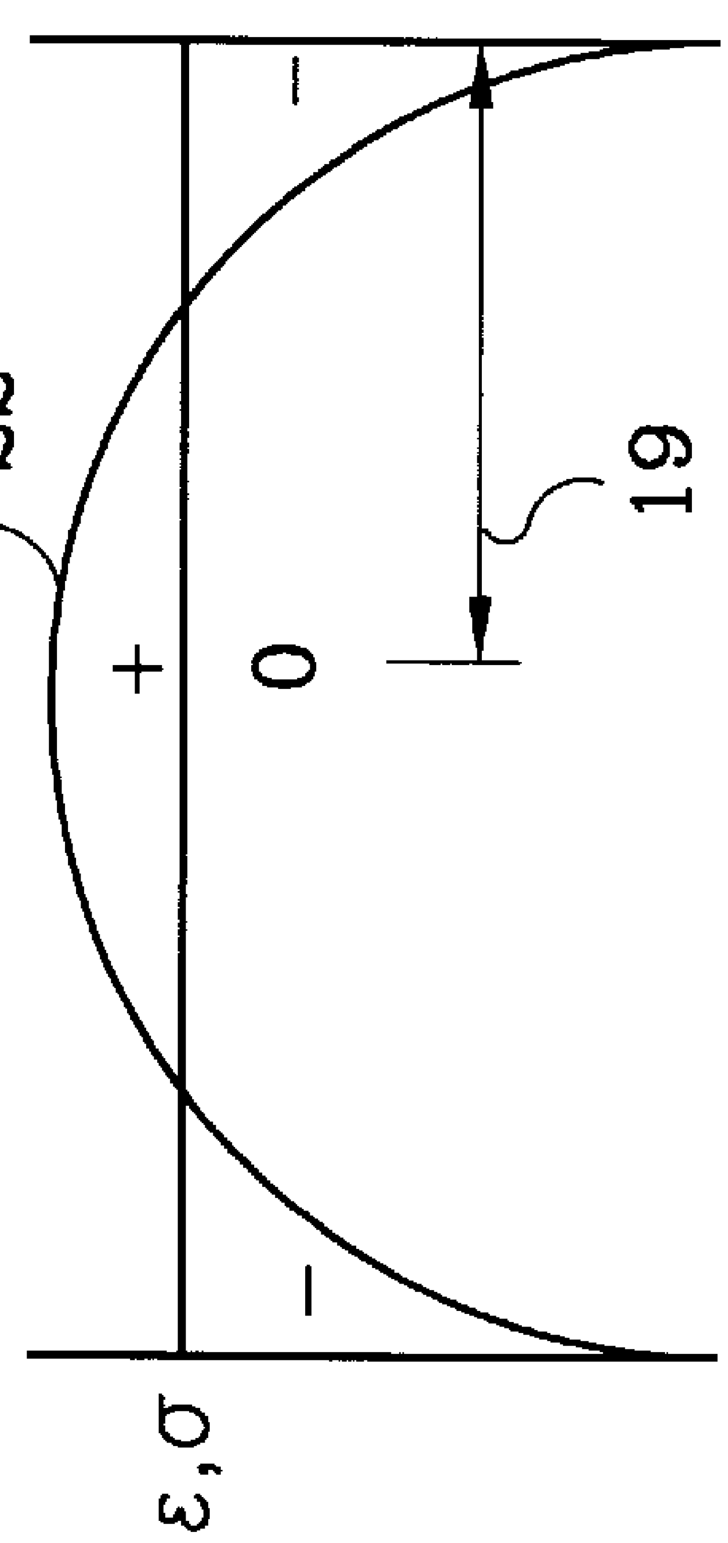


Fig. 2c

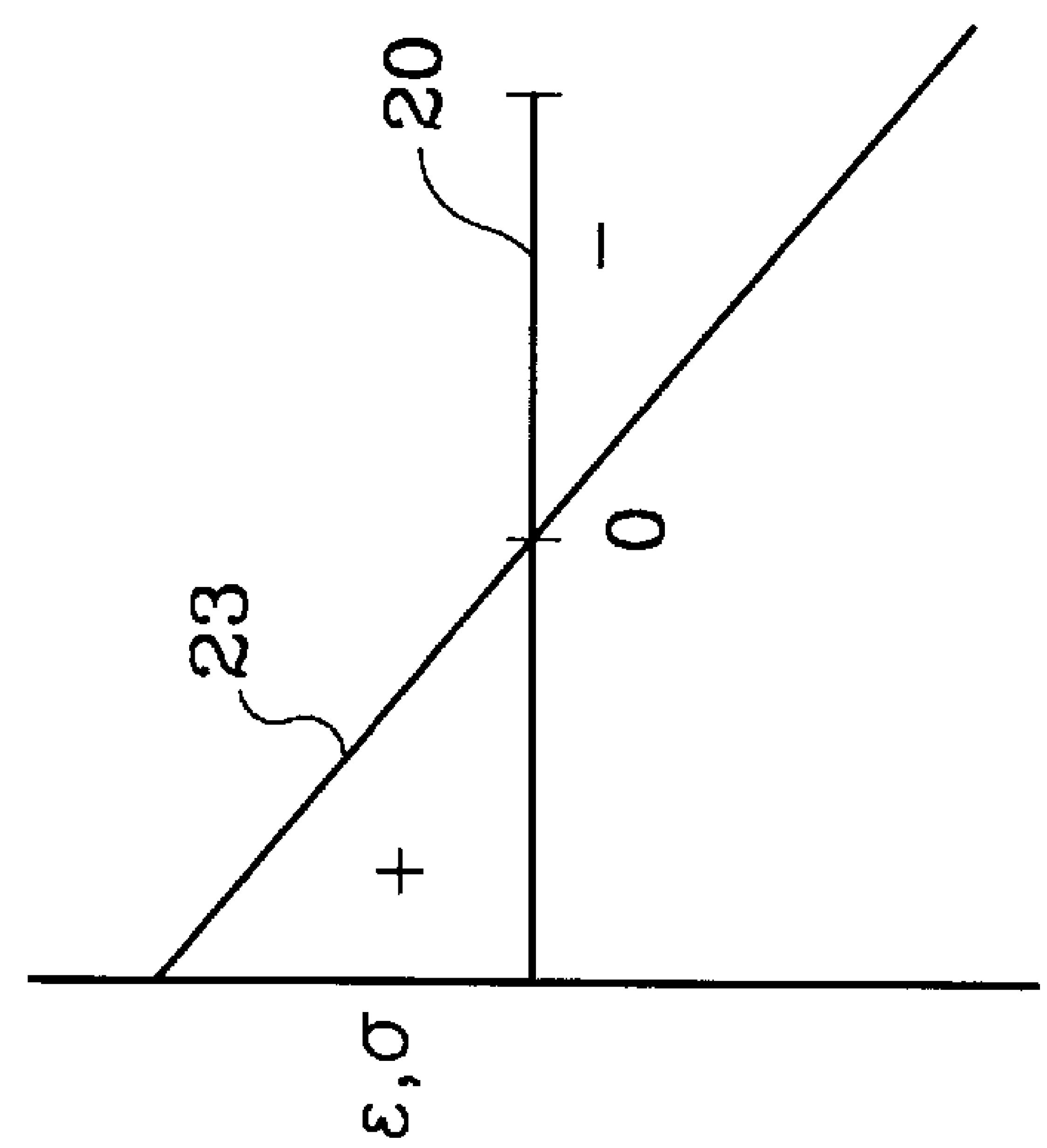


Fig. 2d

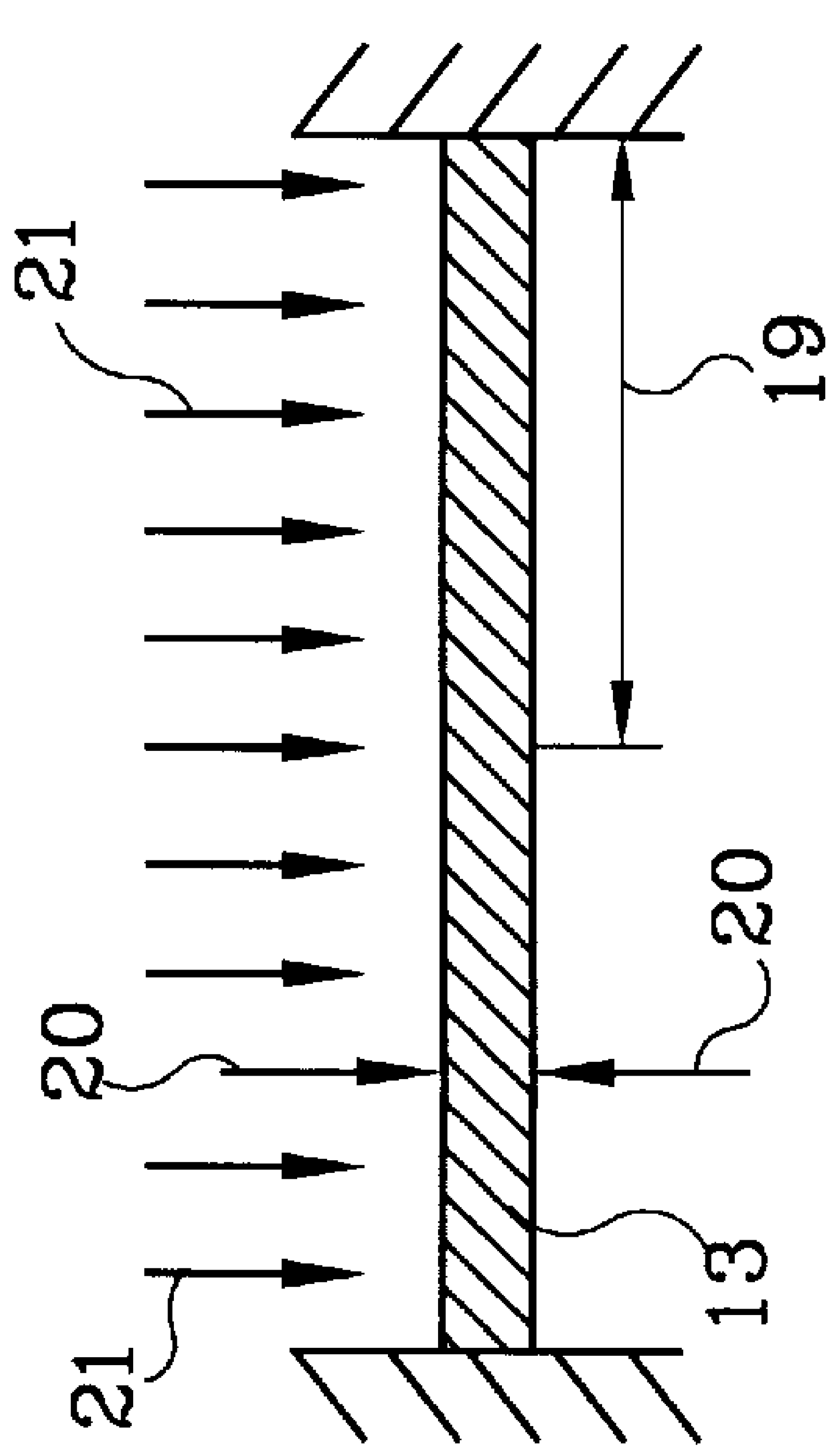


Fig. 2a

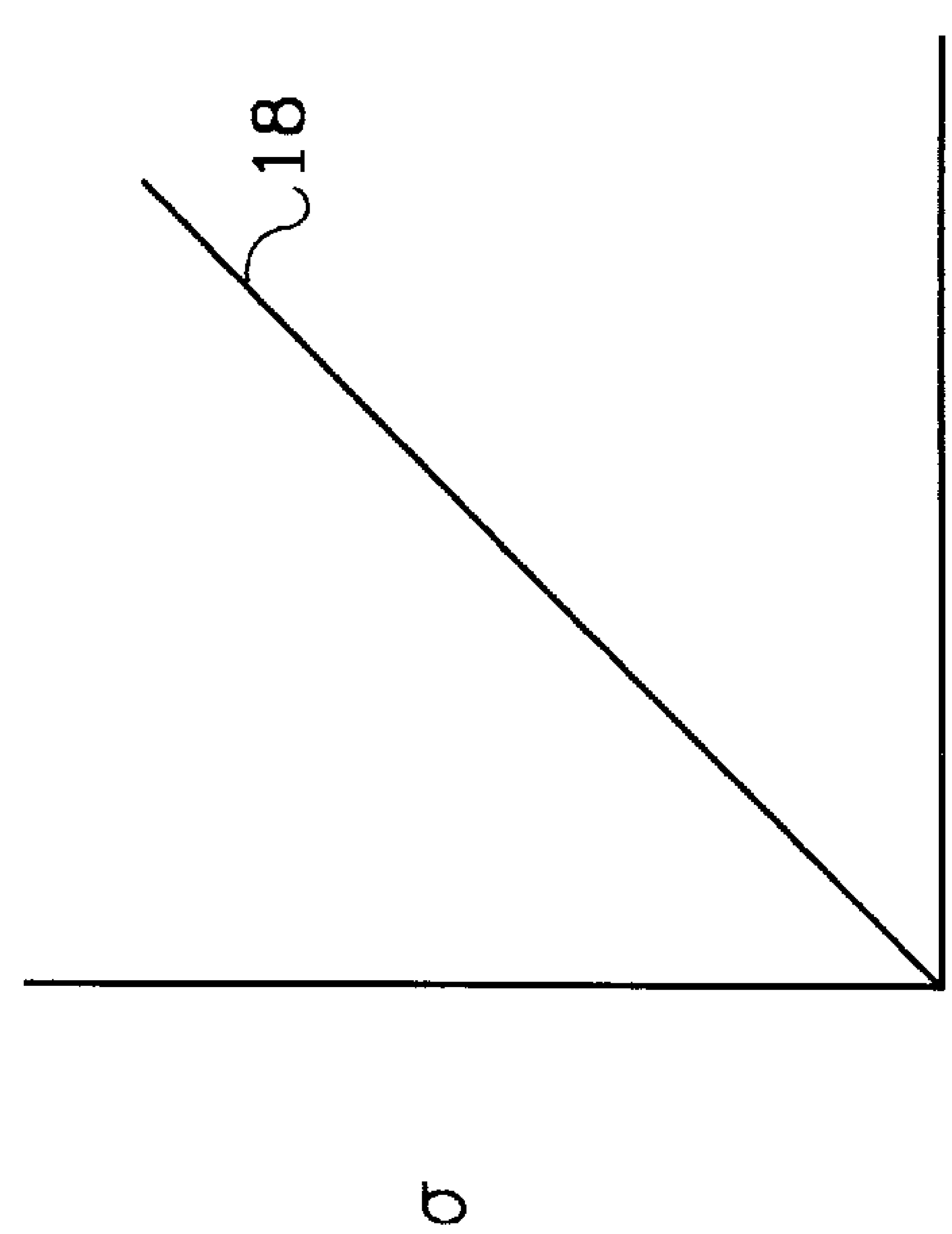


Fig. 2b

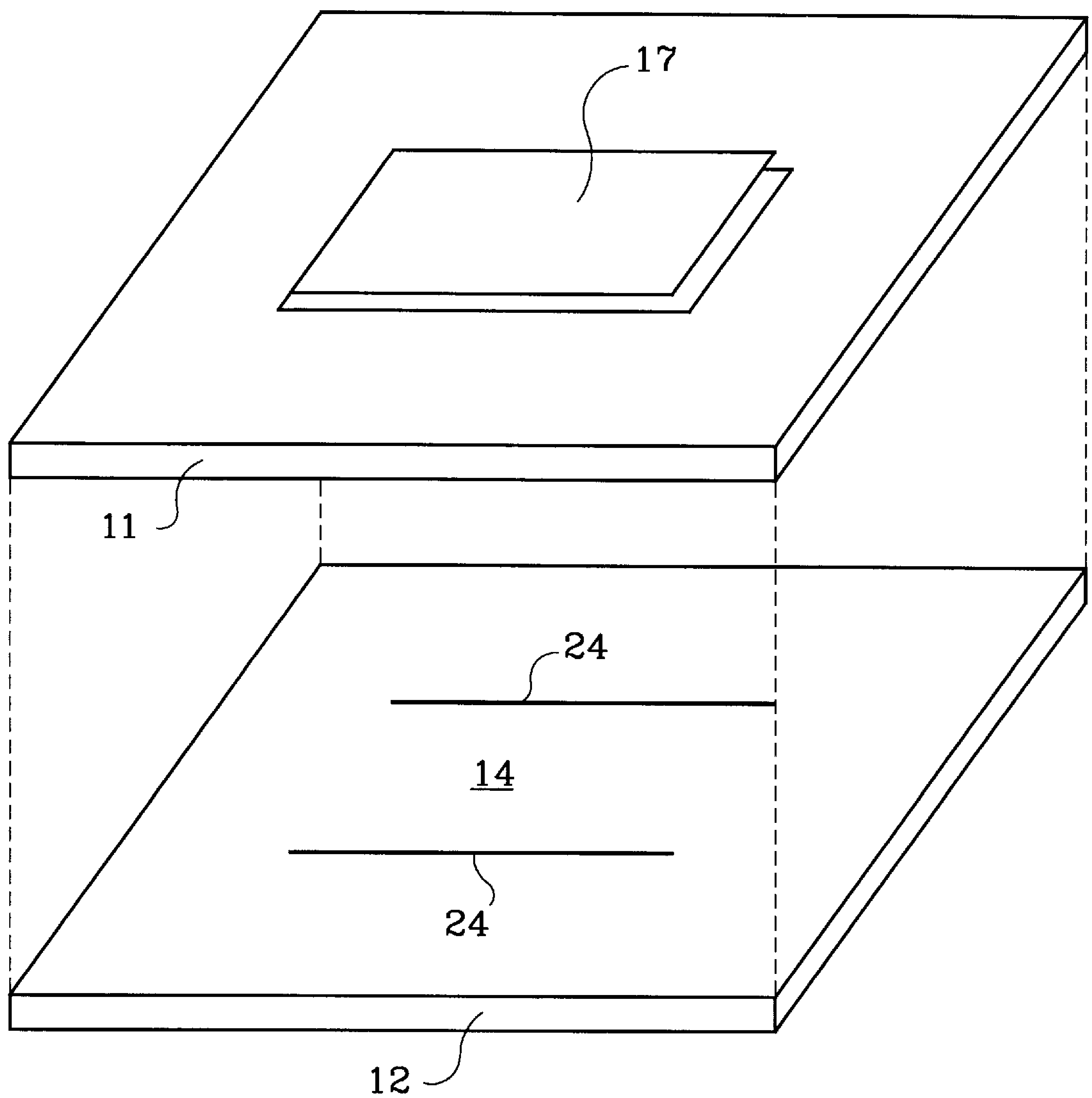


Fig. 3

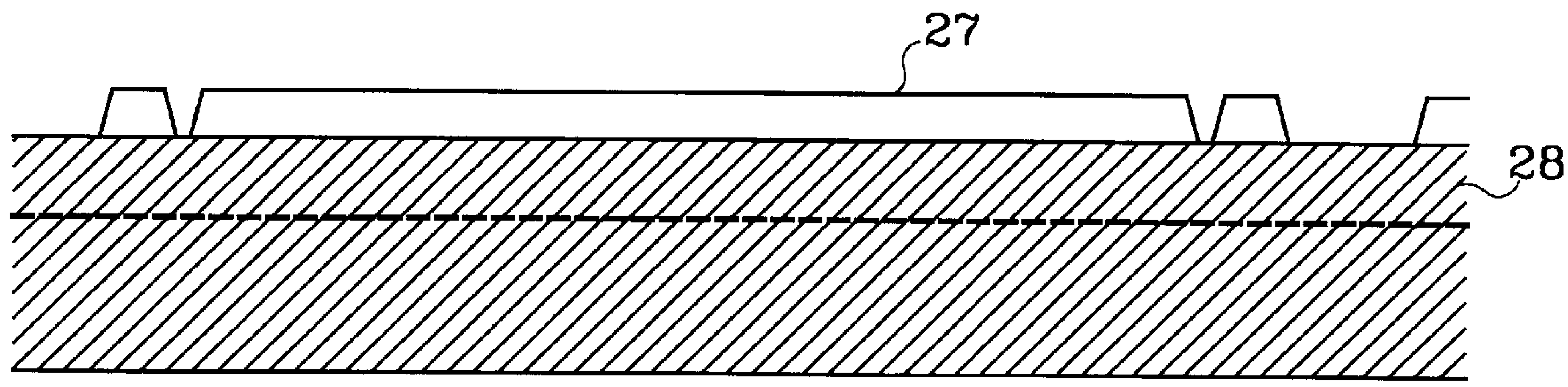


Fig. 4a

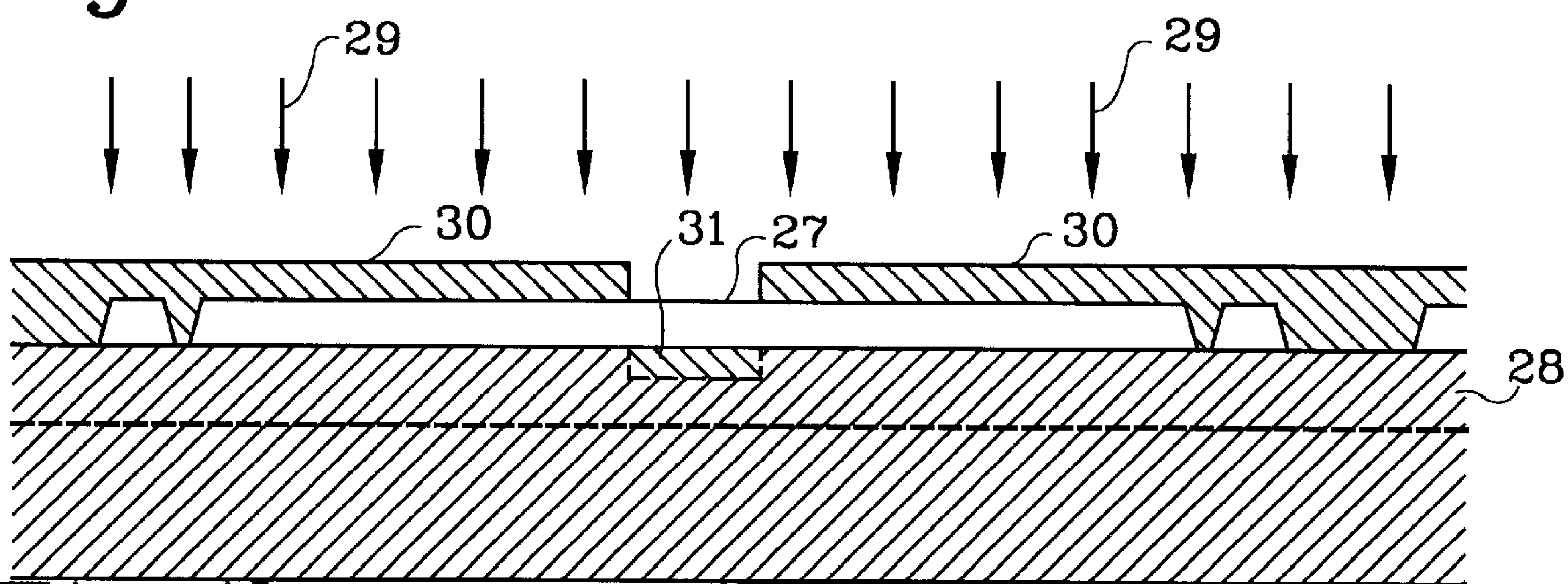


Fig. 4b

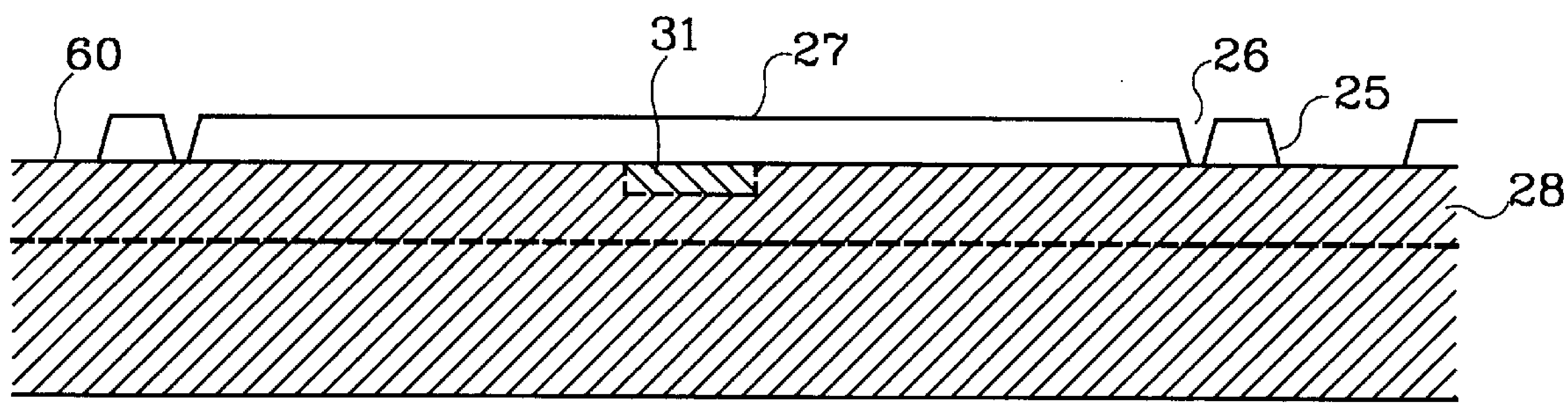


Fig. 4c

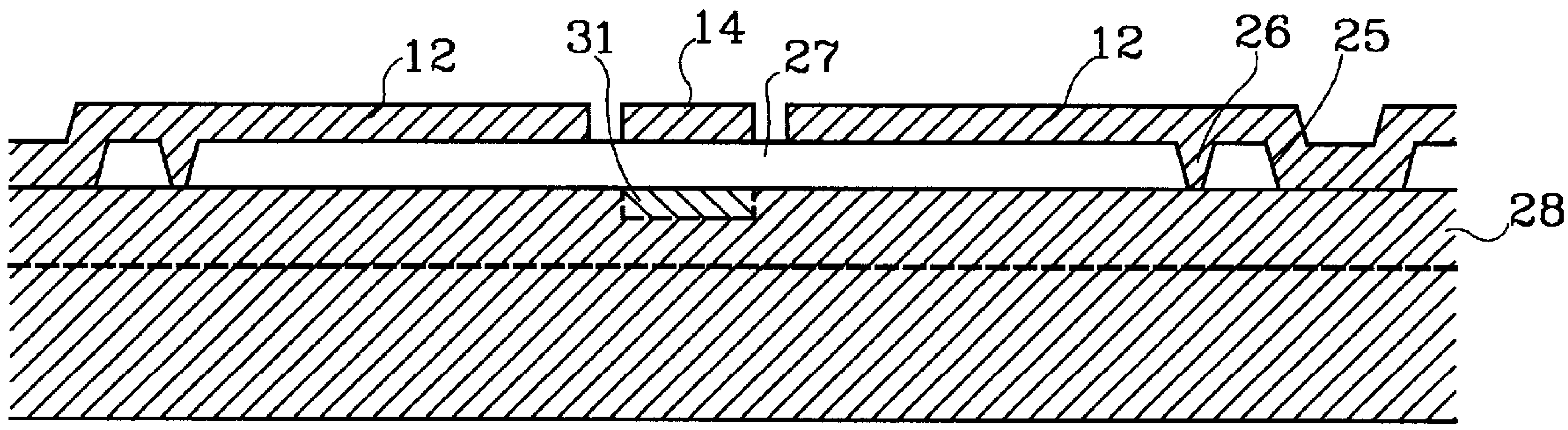


Fig. 4d

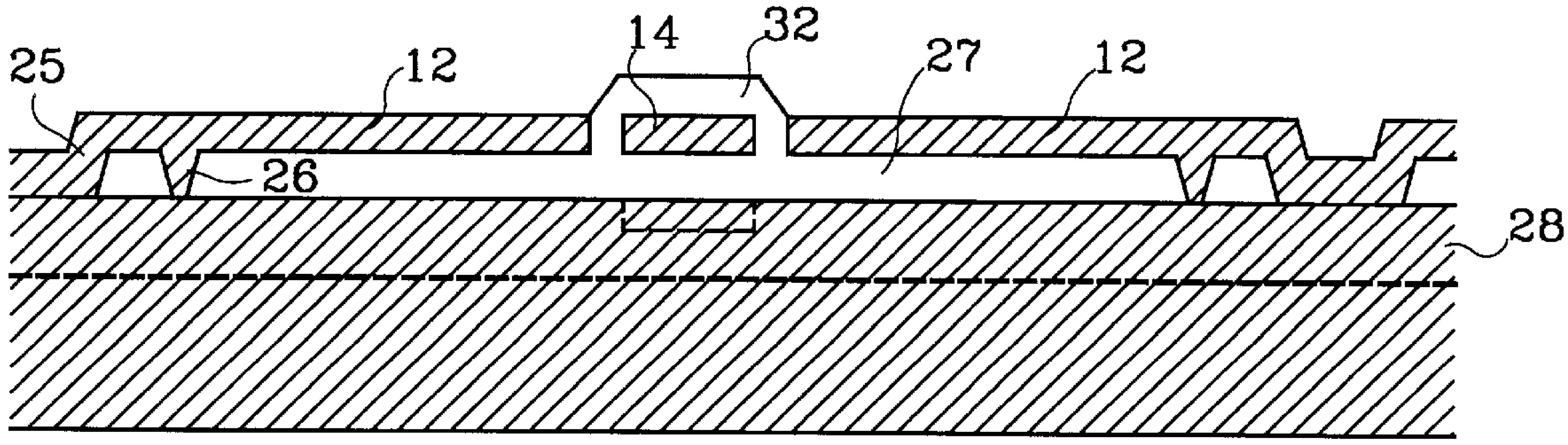


Fig. 4e

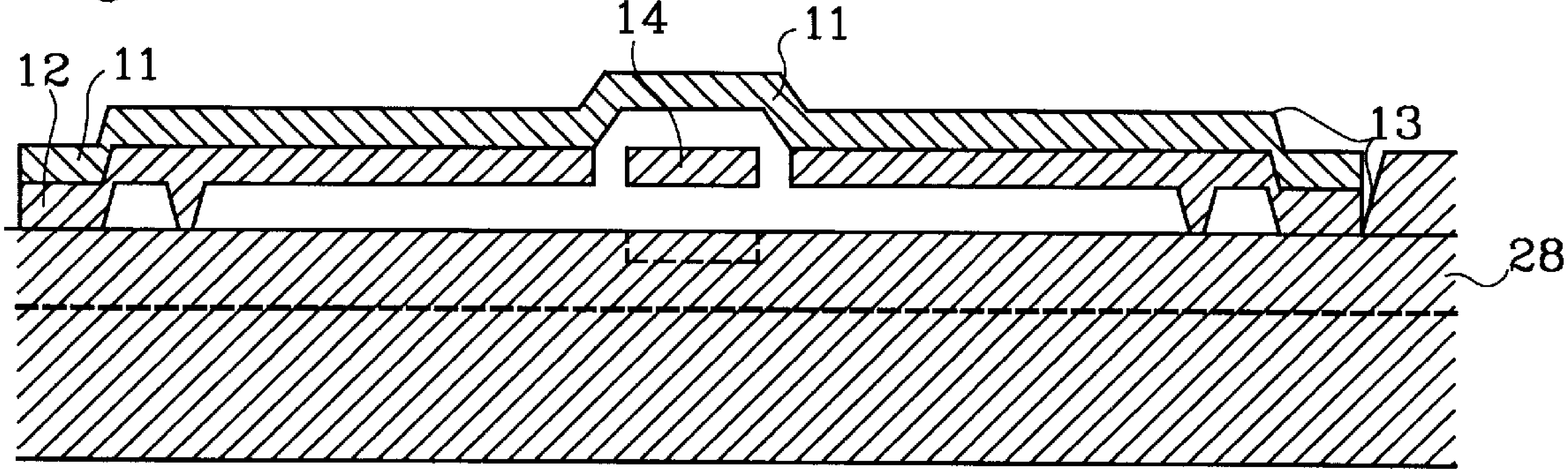


Fig. 4f

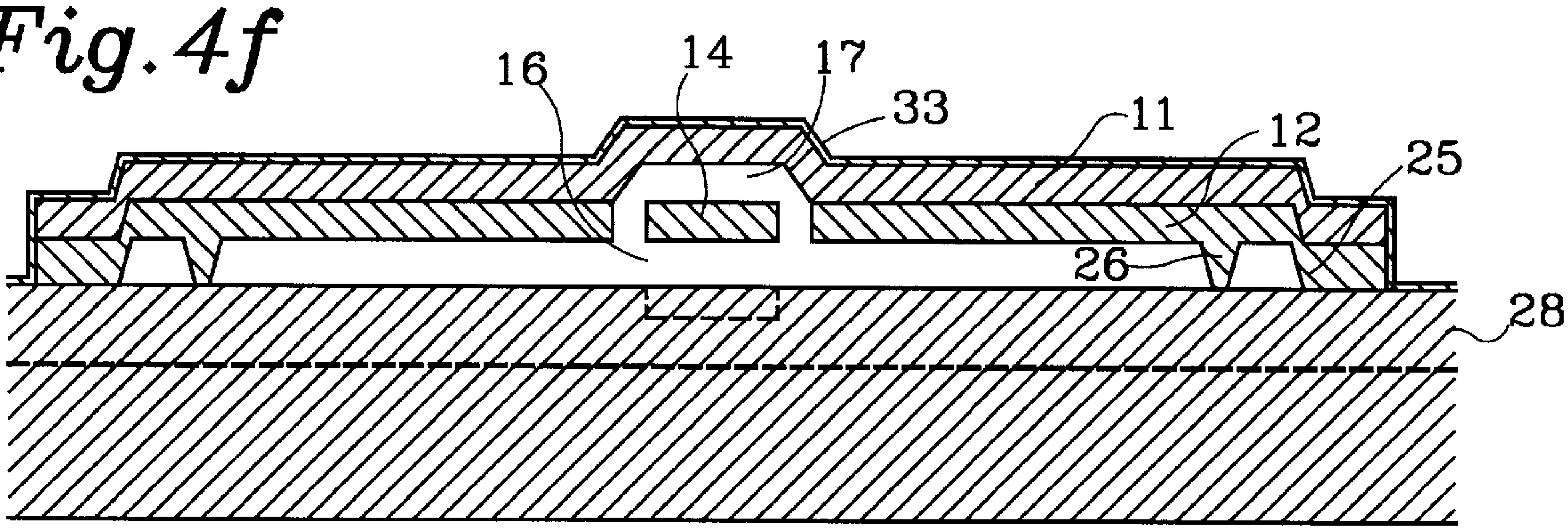


Fig. 4g

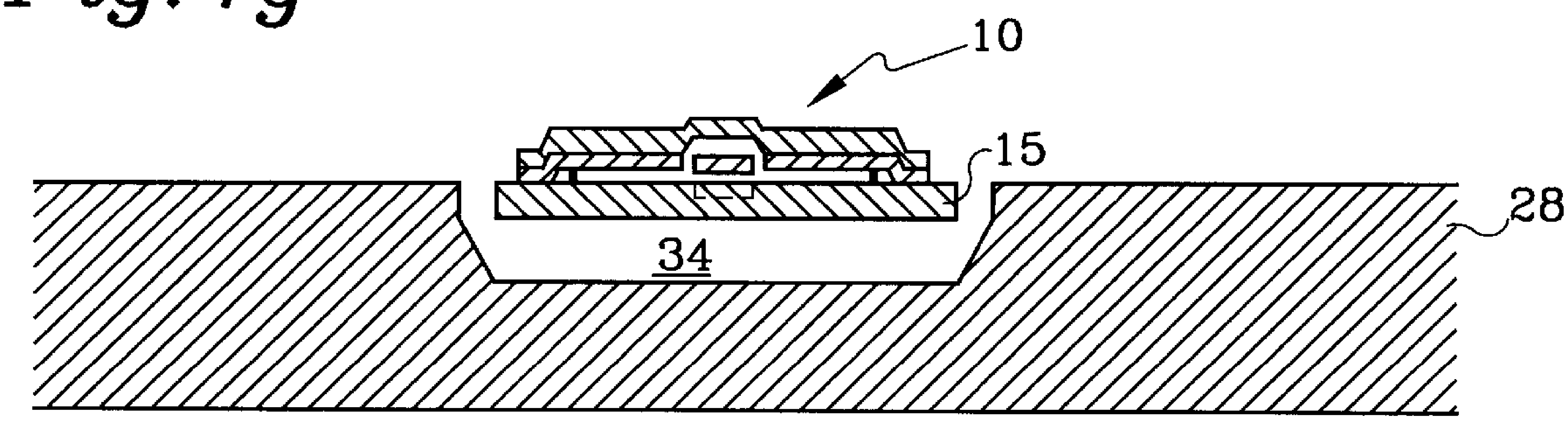


Fig. 4h

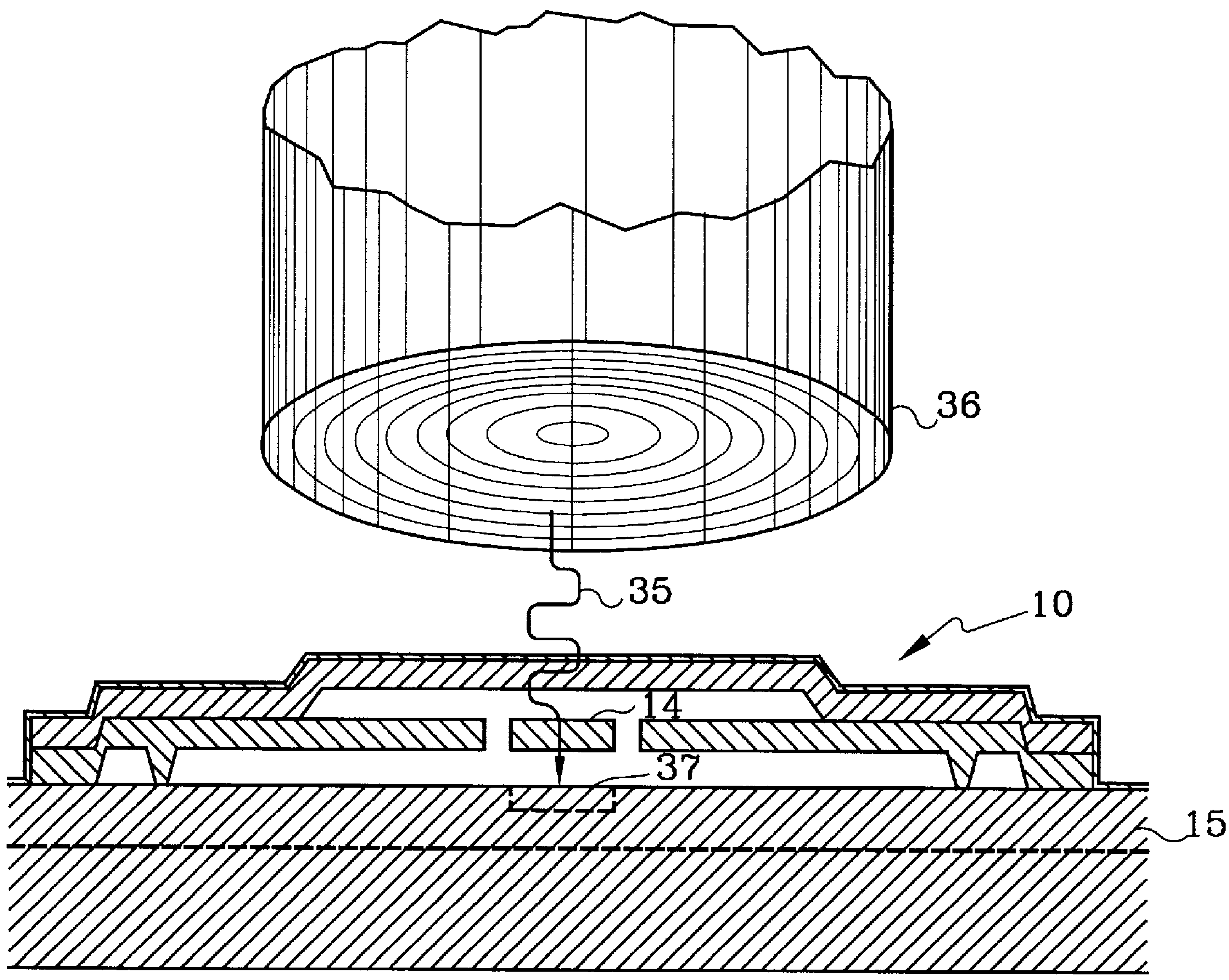


Fig. 5

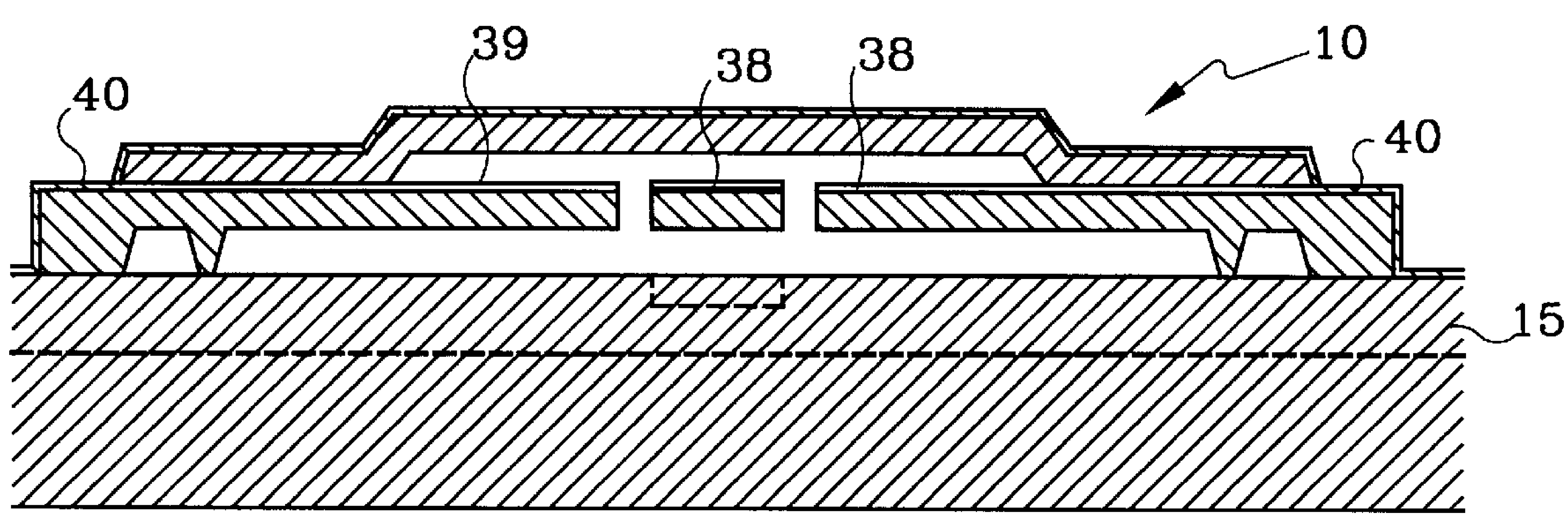


Fig. 6

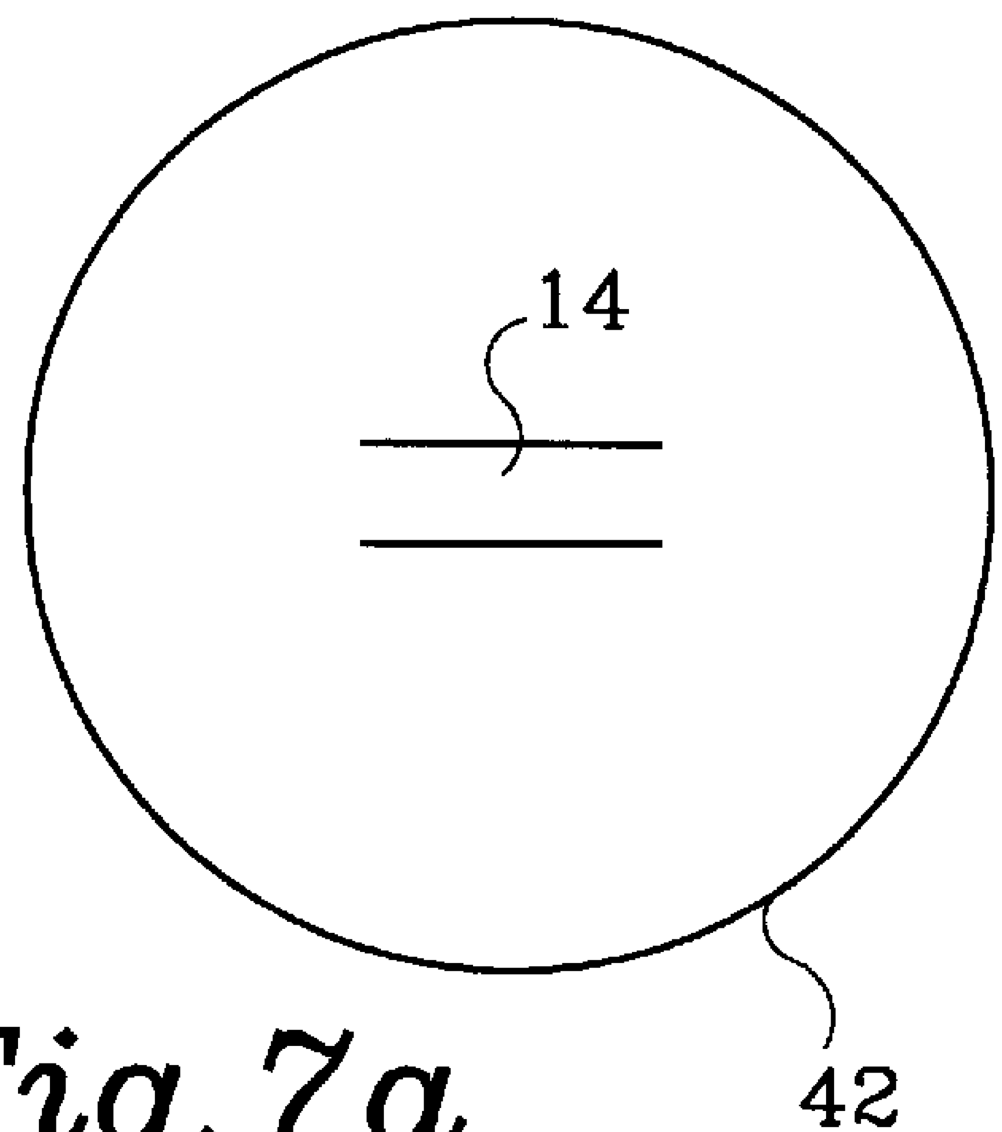


Fig. 7a

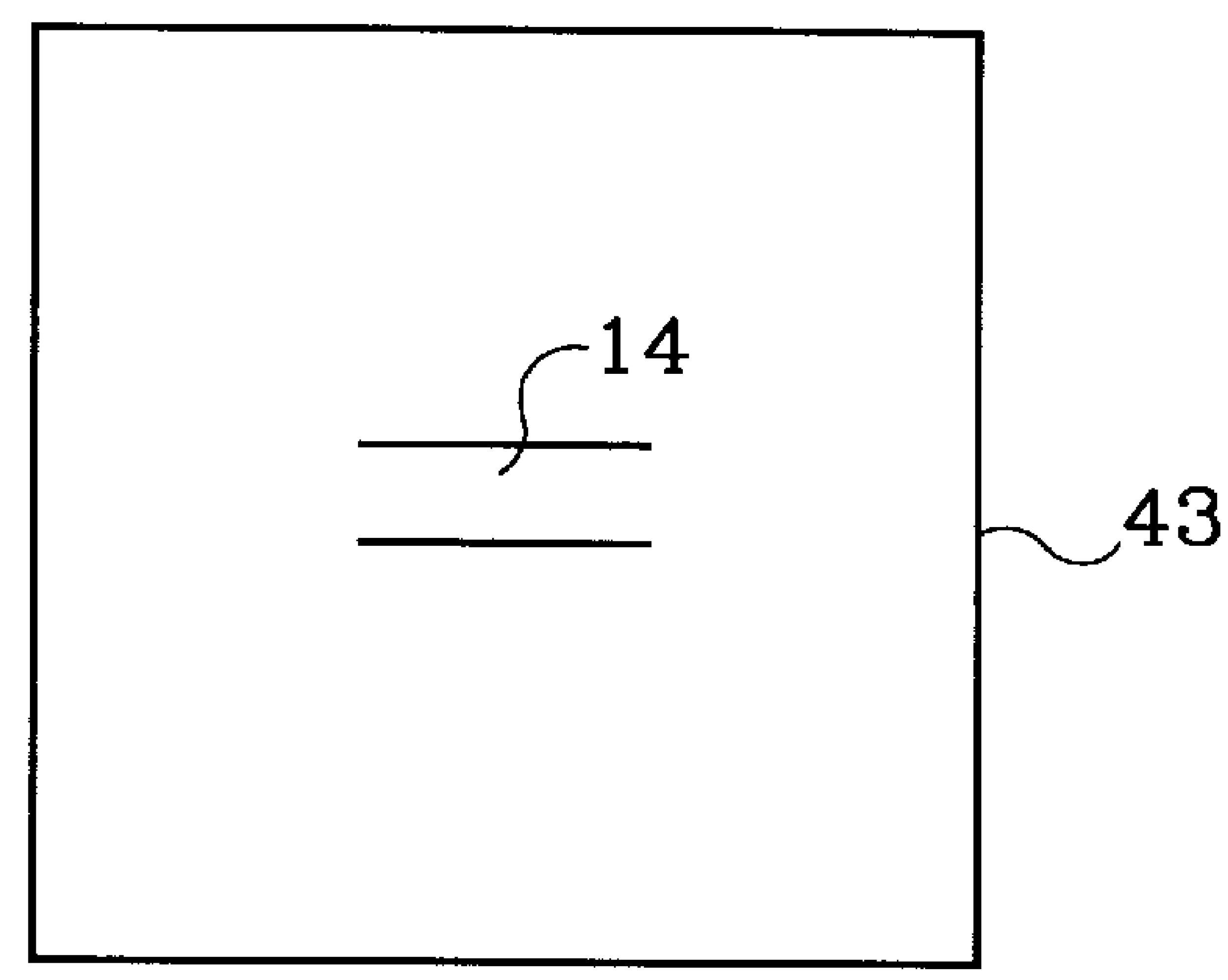


Fig. 7b

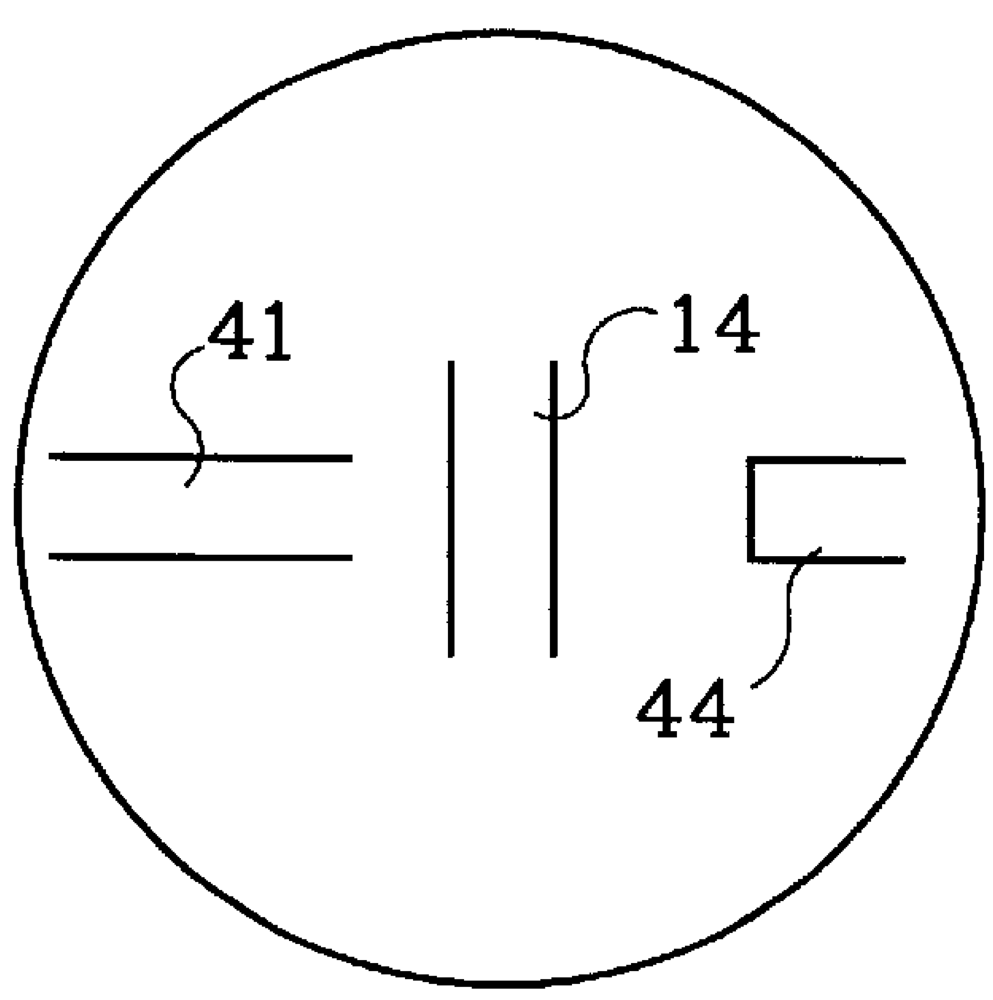


Fig. 8a

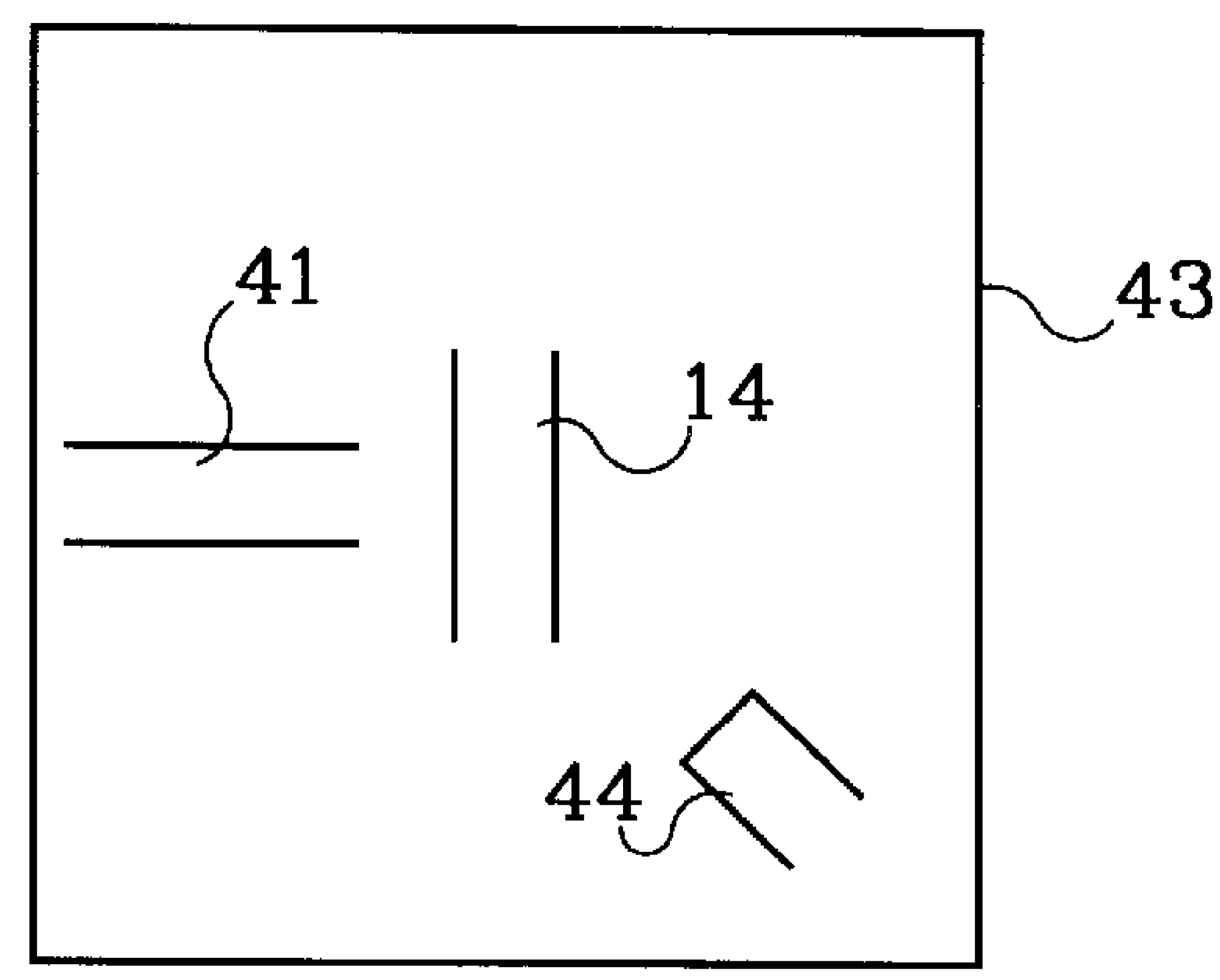


Fig. 8b

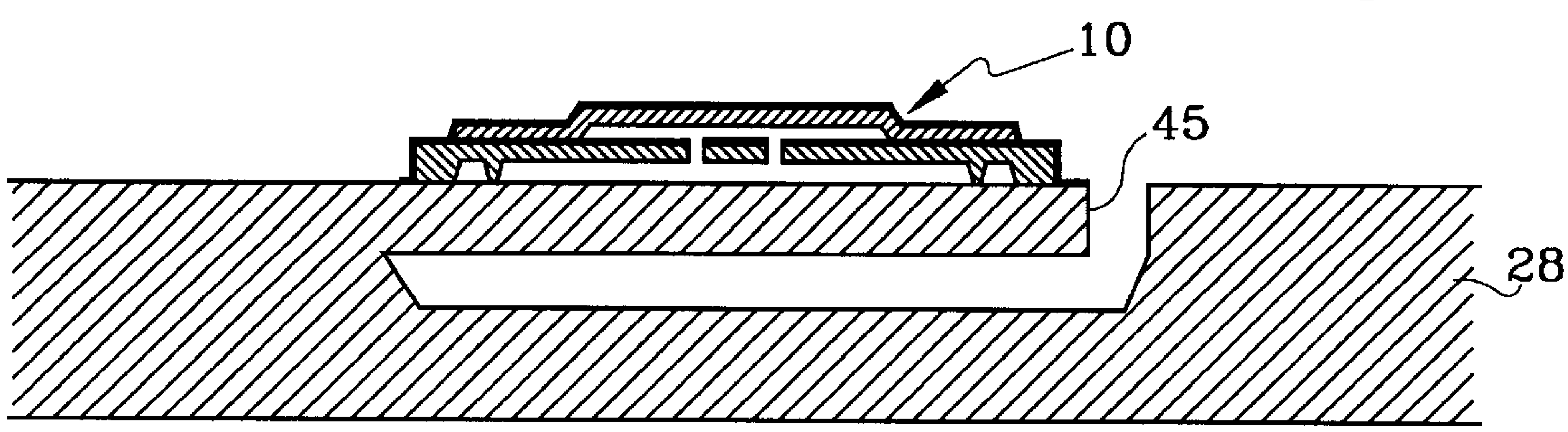


Fig. 9a

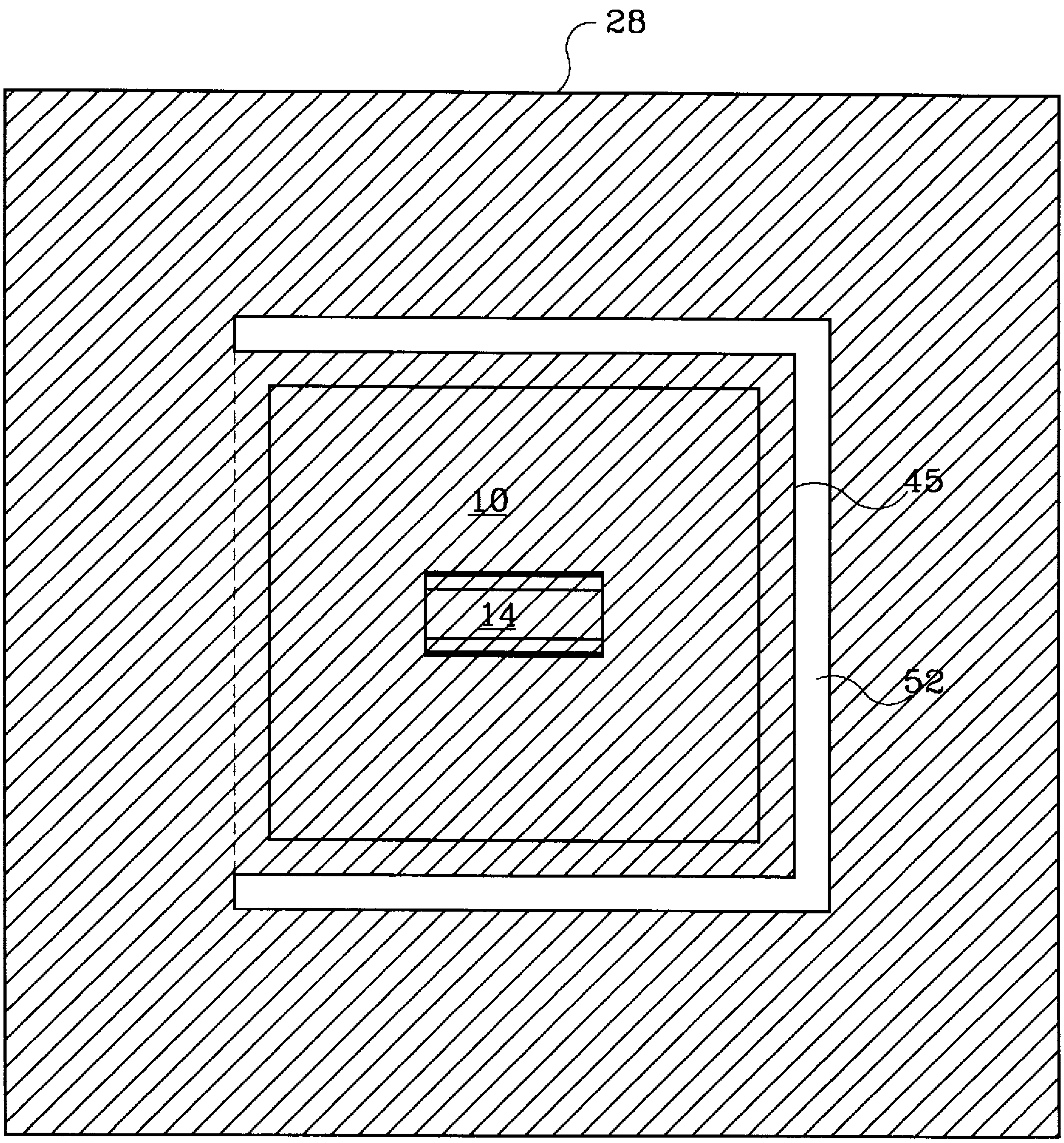


Fig. 9b

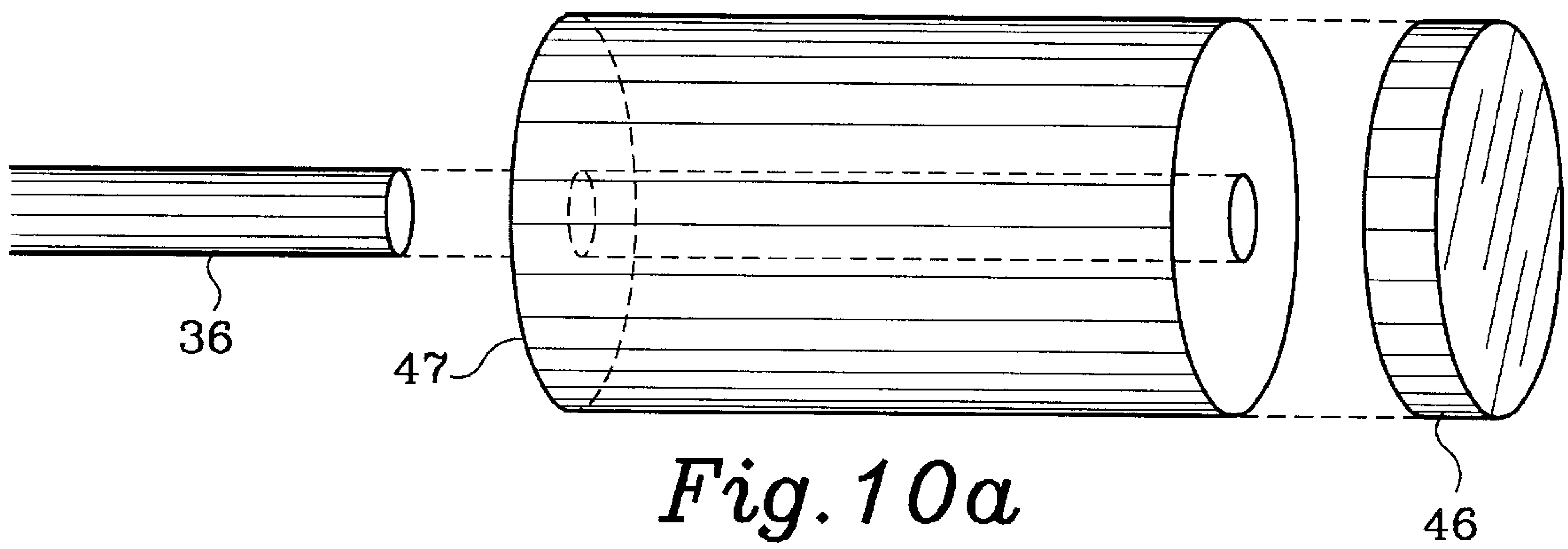


Fig. 10a

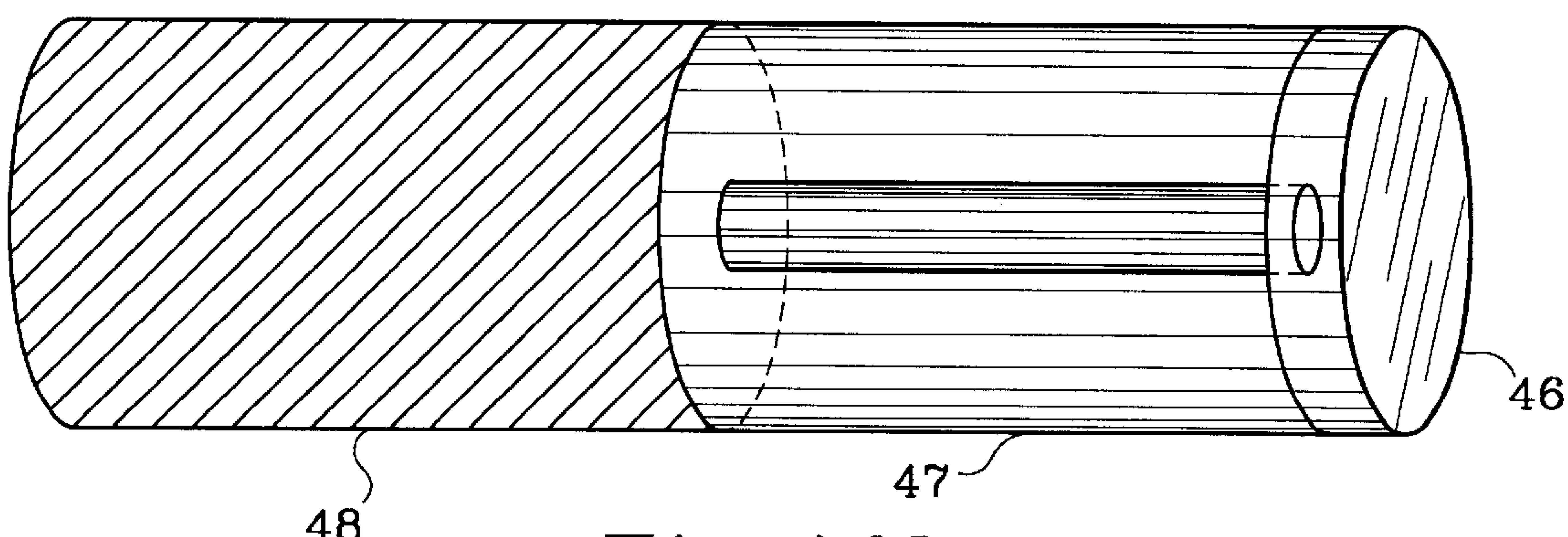


Fig. 10b

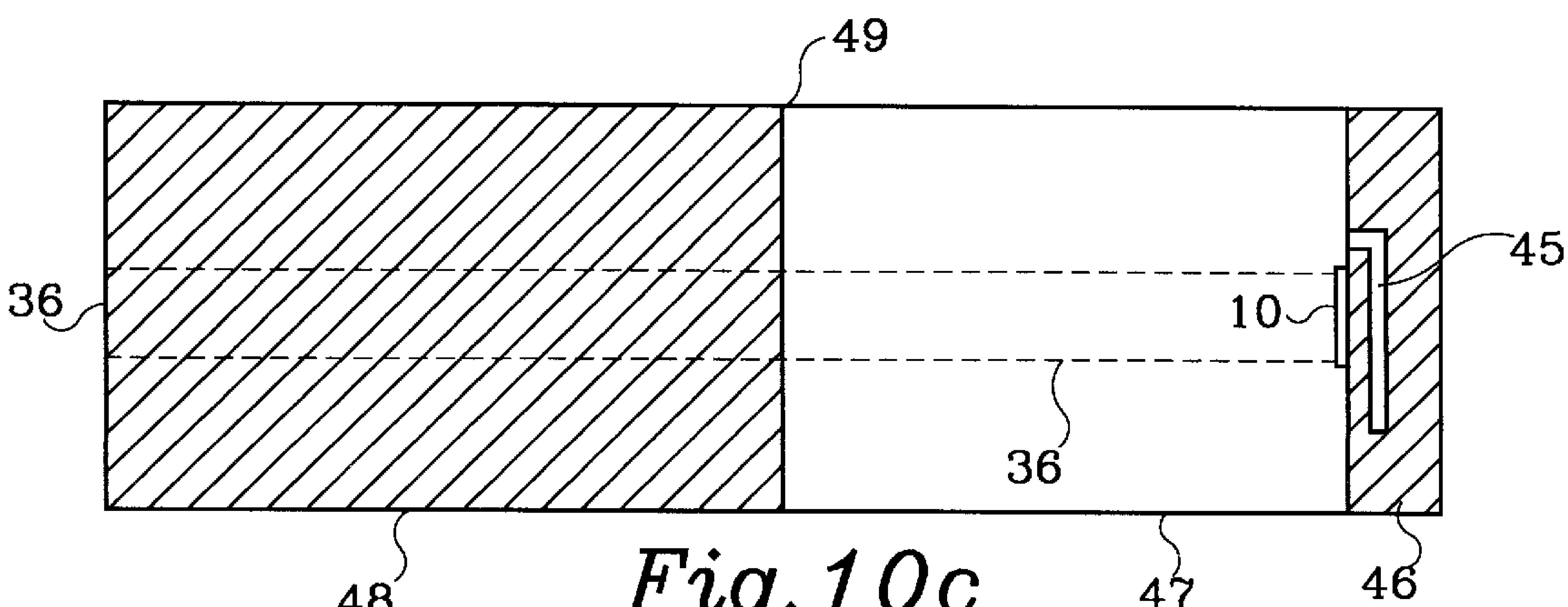


Fig. 10c

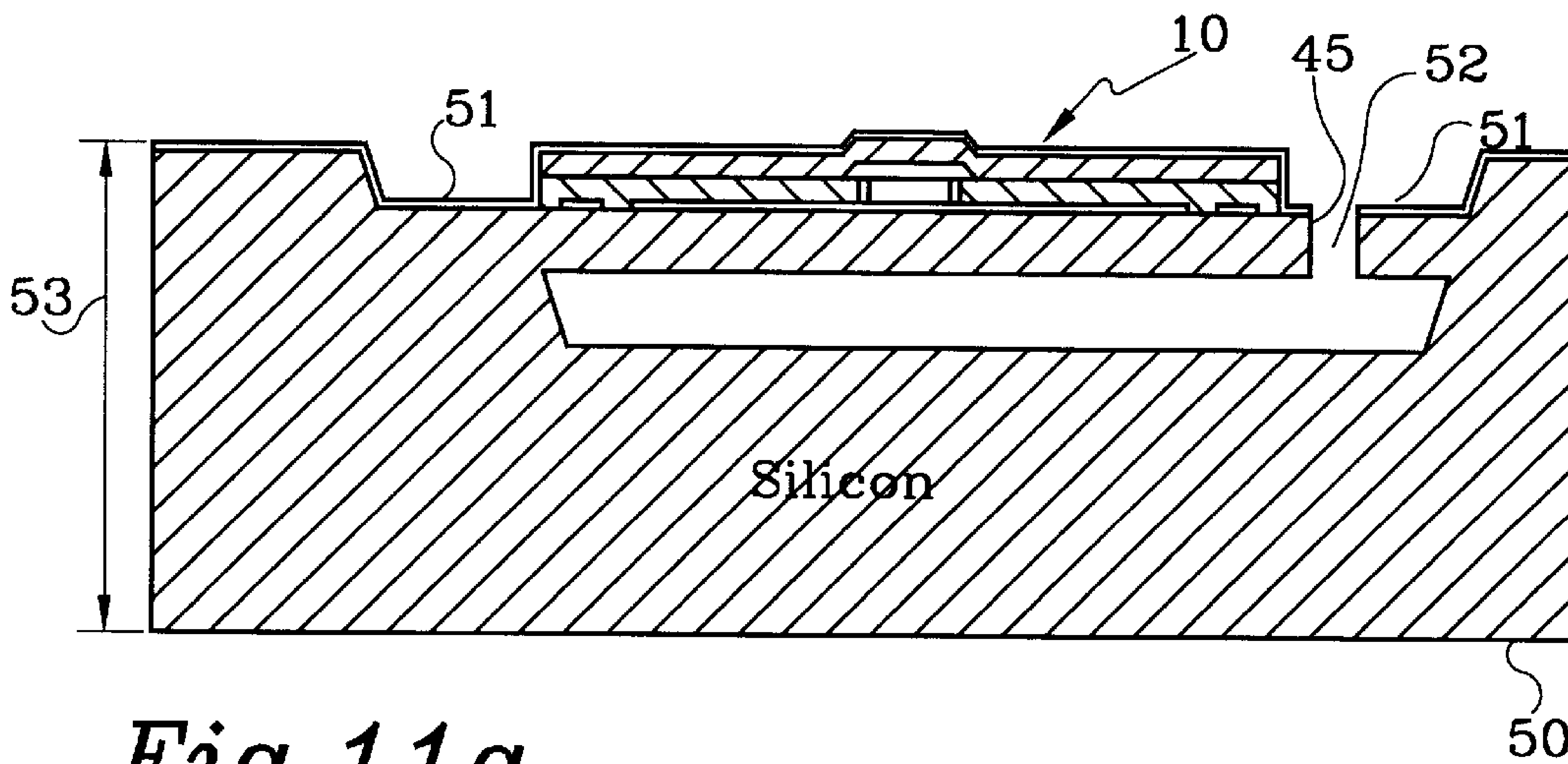


Fig. 11a

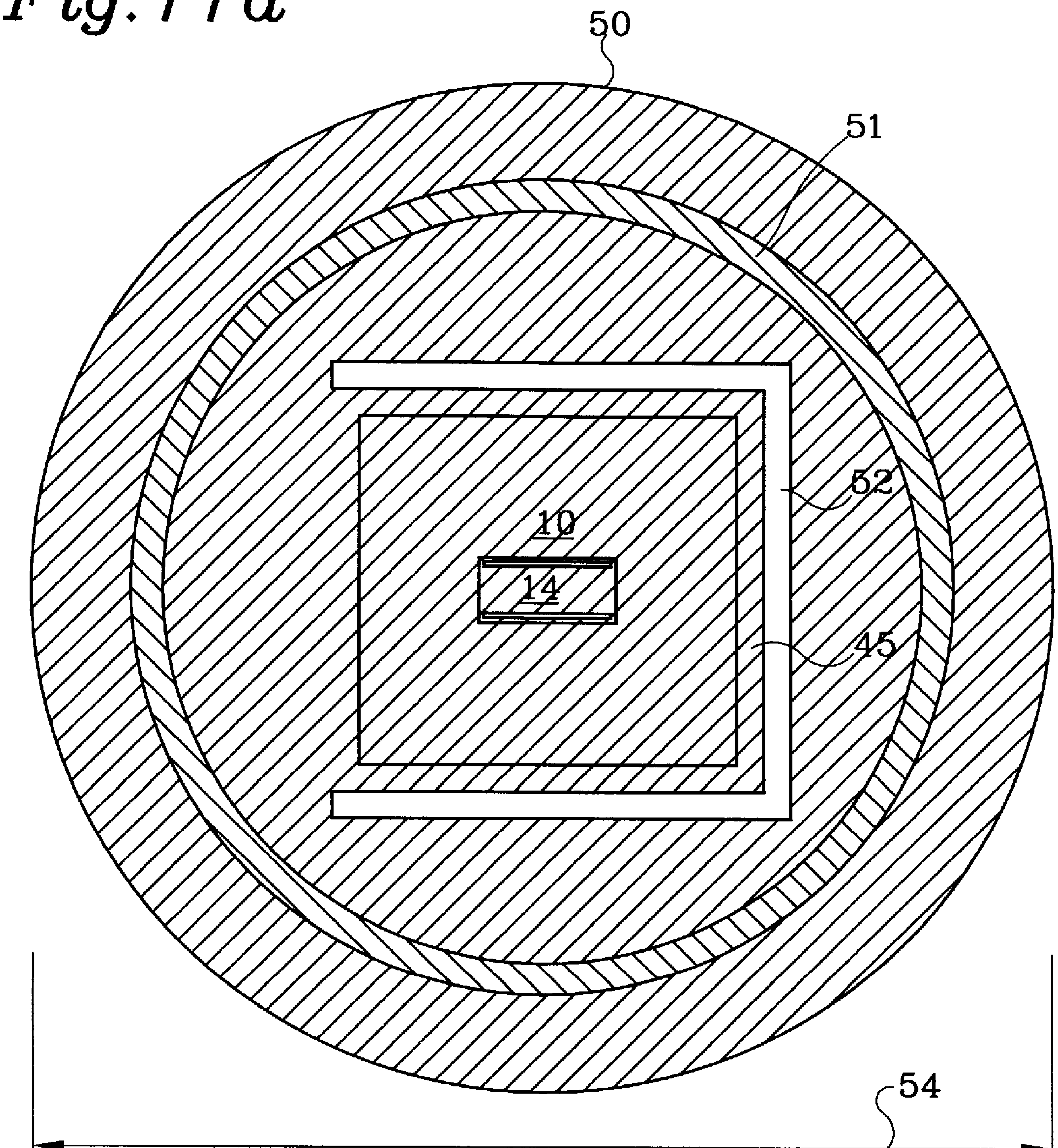


Fig. 11b

THIN FILM RESONANT MICROBEAM ABSOLUTE PRESSURE SENSOR

BACKGROUND OF THE INVENTION

The invention pertains to sensors and particularly to resonant sensors. More particularly, the invention pertains to resonant microbeam pressure sensors having a polysilicon microbeam resonator formed from a portion of the sensor diaphragm.

Previous developments have resulted in surface micromachined pressure sensors each of which had a pressure diaphragm formed from a deposited thin film of polysilicon with an integral vacuum cavity reference directly under the diaphragm. Deformations of the diaphragm with applied pressure caused shifts in a Wheatstone bridge fabricated from polysilicon piezoresistors deposited on the diaphragm resulting in a voltage output indicating the amount of pressure sensed by the sensor. The Wheatstone bridge has a relatively low sensitivity to strain in the diaphragm, and the output voltage requires an analog-to-digital (A/D) conversion to be used in digital systems.

Several patents provide background to the present description. U.S. Pat. No. 4,744,863, by inventors Henry Guckel and David W. Burns, issued May 17, 1988, and entitled "Sealed cavity semiconductor pressure transducers and method of producing the same;" U.S. Pat. No. 5,417,115, by inventor David W. Burns, issued May 23, 1995, and entitled "Dielectrically isolated resonant microsensors;" U.S. Pat. No. 5,458,000, by inventors David W. Burns and J. David Zook, issued Oct. 17, 1995, and entitled "Static pressure compensation of resonant integrated microbeam sensors;" and U.S. Pat. No. 5,511,427, by inventor David W. Burns, issued Apr. 30, 1996, and entitled "Cantilevered microbeam temperature sensor" are hereby incorporated in this description by reference.

SUMMARY OF THE INVENTION

The present invention has an integral vacuum cavity reference and a polysilicon diaphragm, but has a polysilicon resonator integrally formed from a portion of the diaphragm, thus being able to provide a frequency output that is a direct measure of the pressure applied to the top surface of the diaphragm, thus eliminating the errors of the Wheatstone or other parameter transforming device deposited on the diaphragm which introduces errors into the results of the measured parameter. The output of the present micromachined sensor interfaces readily with digital and optical systems. The invention is a thin film resonant microbeam absolute pressure sensor that achieves the advantageous objectives of having an integral vacuum reference, a frequency output, high sensitivity and integral stress isolation. Fabrication of this microbeam sensor requires no backside wafer processing, involves a process and layout independent of wafer thickness, can use full thickness die for high yield and robustness, and the process is compatible with a family of resonant sensors (including temperature and strain).

The invention is a microstructure having a thin film diaphragm, at least one embedded resonator, and an integral vacuum reference. The diaphragm and resonator are formed from polysilicon. This sensor may utilize a sensing and driving mechanism that is either electrical or optical, or a combination of electrical and optical. The sensor may have a single resonant microbeam or a multiple of microbeams which may include push-pull operation for temperature cancellation or compensation.

For more precise sensing, the microbeam sensor may incorporate integral stress isolation using cantilevered single crystal silicon paddles. The sensor may be configured into a differential pressure sensor by a process that uses additional micromachining while retaining the resonator in its own vacuum reference.

BRIEF DESCRIPTION OF THE DRAWING

FIG. **1** shows a resonant microbeam pressure sensor.

FIGS. **2***a*, **2***b*, **2***c* and **2***d* illustrate the stress effects on a pressure sensing diaphragm.

FIG. **3** is a schematic of a resonant microbeam sensor diaphragm.

FIGS. **4***a*, **4***b*, **4***c*, **4***d*, **4***e*, **4***f*, **4***g* and **4***h* show a process for fabricating a resonant microbeam sensor.

FIG. **5** reveals an optically driven resonant microbeam sensor.

FIG. **6** illustrates an electrically driven resonant microbeam sensor having an electrostatic drive line and a piezoresistive sense line.

FIGS. **7***a*, **7***b*, **8***a* and **8***b* show single and multiple resonator configurations, respectively.

FIGS. **9***a* and **9***b* reveal a stress isolating mounting for a resonant microbeam sensor.

FIGS. **10***a*, **10***b* and **10***c* illustrate a resonant microbeam sensor having a fiber optic drive and sense mechanism.

FIGS. **11***a* and **11***b* show a recessed stress isolating mounting for a microbeam sensor.

DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. **1** shows a cross-section of the present thin film resonant microbeam absolute pressure sensor **10**. Two layers **11** and **12** of fine-grained polysilicon form pressure sensitive diaphragm **13**, with a resonant member **14** formed in lower layer **12**. Composite diaphragm **13** is fabricated on a silicon substrate **15**. Using surface micromachining techniques, sacrificial oxides and reactive sealing, a vacuum cavity reference **16** is formed in the region between diaphragm **13** and substrate **15**. Pressure applied to the topside of diaphragm **13** creates deformations into lower cavity region **16**, stretching resonant microbeam **14** and causing shifts in its resonant frequency. Microbeam **14** is free to vibrate into lower cavity region **16** and into an upper cavity region **17** (also in vacuum). Optical or electrical drive mechanisms excite the microbeam into resonance and detection of the vibration provides a quasi-digital output signal which is a measure of applied pressure. Multiple resonators can be configured on a single diaphragm **13** to provide compensation for temperature and common mode effects. Diaphragm **13** can be circular or square; similarly, so can the die. An optional fabrication sequence using B:Ge codoped material provides significant stress isolation by undercutting silicon substrate **15** directly beneath the pressure sensor. Other micromachining steps can adapt resonant pressure sensor **10** to differential pressure sensor sensing applications using multiple devices or by configuring an additional pressure port.

This device has a pressure diaphragm formed from a deposited thin film of polysilicon, with an integral vacuum reference directly underneath the diaphragm. Deformations of the diaphragm with applied pressure caused resistance shifts of a Wheatstone bridge, fabricated from polysilicon piezoresistors deposited on the diaphragm. Device **10** described here has an integral vacuum cavity **16** reference and a polysilicon diaphragm **13**, but has a polysilicon resonator **14** integrally formed from a portion of diaphragm **13**, thus providing a frequency output that is a direct measure of pressure applied to the top surface of diaphragm **13** (see FIG. **1**) which interfaces readily with digital and optical systems.

Operation of device **10** can be noted by inspecting the illustrations in FIGS. **2***a*, **2***b*, **2***c* and **2***d*. Deformations of pressure-sensitive diaphragm **13** with applied pressure (P_{app}) creates stress (σ_{max}) in the plane of diaphragm **13** which increases linearly with pressure, for small deflections as shown by curve **18** in FIG. **2***b*. The stress σ and strain & distributions in the plane of diaphragm **13**, however, vary for points near the edge of diaphragm **13** or near the center. The stress (or strain) distribution at the bottom of diaphragm **13** is tensile near the center and compressive near the periphery.

FIG. **2***c* shows stress and strain distributions of a diaphragm **13** based pressure sensor **10**. A fully supported diaphragm **13** of radius **19** (h) and thickness **20** is shown in FIG. **2***a* with pressure applied to the topside. The maximum tensile stress occurs at the diaphragm **13** edge, and increases linearly with applied pressure (in FIG. **2***b*). The stress distribution at the bottom of the diaphragm **13** varies, according to curve **22** of FIG. **2***c*, from a tensile stress at the center to a compressive stress at the periphery, indicating that a resonator **14** is appropriately placed either at the diaphragm **13** center, or at the periphery. FIG. **2***d* shows the stress and strain profile **23** with diaphragm **13** thickness **20**, with a compressive stress at the upper surface and a tensile stress at the lower surface.

Resonant pressure sensors have been designed and fabricated with resonant microbeams fabricated on single crystal silicon diaphragms. Smaller size, large signal and an integral vacuum reference **16** is obtained by the methods and innovation described here. The single crystal silicon diaphragm is replaced with a much smaller (100 to 500 micrometers) polysilicon diaphragm **13**, varying from 1.0 to 5.0 micron thick. Diaphragm **13** is formed from two layers **11** and **12** of polysilicon, as shown in FIG. **3**. Resonator **14** is formed by etching two slits **24** in lower (beam) polysilicon layer **12**. Upper (shell) polysilicon layer **11** increases diaphragm **13** thickness and contains a small cavity **17** directly above microbeam **14** to allow it to vibrate unencumbered. Vacuum reference cavity **16** is located underneath lower polysilicon layer **12**. Anchor regions **25** and **26**, shown in FIGS. **1**, **5** and **6**, allow diaphragm **13** to replicate as closely as possible clamped boundary conditions at the periphery. These consist of relatively wide anchor regions **25** for the outside of the plate, and segmented, narrow inner regions **26** for firming the displacements at the periphery.

The number of masking levels required for resonant absolute pressure sensor **10** is six: lower cavity masking level, lower drive, channel, beam, upper cavity and shell. Additional levels are required to form paddle-style stress isolation (described below) and piezoresistive or capacitive sense.

The lower cavity mask forms region **16** for the vacuum reference and allows mechanical contact between the periphery of diaphragm **13** and underlying substrate **15** through the lower cavity sacrificial oxide. The lower drive level is used to form photodiodes **31** in substrate **15** directly beneath microbeam **14**. The photodiodes will create an electric field due to the photovoltaic effect when stimulated by incident radiation and allow optical interrogation of microbeam frequencies. This layer can similarly be used to form drive or sense electrodes in substrate **15** for electrical versions. The channel layer is used to provide access **60** for liquid access of etchant to the upper and lower cavities for removal of the sacrificial material. The channels are required to be thin for sealing purposes. The beam layer is used to define resonators. The upper cavity layer is used to pattern the upper cavity oxide immediately above resonators **14**. Shell layer defines diaphragm **13** and completes the vacuum enclosure for microbeam **14**. The upper cavity **17**, beam **14** and shell thicknesses are chosen to intensity modulate the sensing radiation for optical detection and excitation. An optional trench mask is used to define a U-shaped trench around three sides of the paddles for stress isolation.

The microbeam fabrication process (see FIGS. **4***a*, **4***b*, **4***c*, **4***d*, **4***e*, **4***f*, **4***g* and **4***h*) contains three LTO deposition steps and two polysilicon deposition steps. Three implants are used; two of them are blanket implants. No thermal oxidations are required in this sequence. Silicon nitride is used for an antireflection coating and a scratch protection layer. Processing of optically resonant microbeams **14** begins with a nominally 7500 angstrom deposition of LTO **27** (i.e., low temperature oxide) on a silicon wafer **28** in FIG. **4***a*. Wafers **28** are n- or p-type with (optional) inclusion of an epitaxial layer on top of a codoped B:Ge etch stop layer. LTO **27** is patterned and etched using the lower cavity masking level to anchor diaphragm **13** to substrate **15** and define the vacuum cavity reference region. An implant **29** is done through oxide **27** with a PR mask **30** of the lower drive layer to form p-n junctions **31** in substrate **28** of FIG. **4***b*. A thin, nominally 800 angstrom LTO layer is deposited and patterned with the channel layer to form etch channels **60** to and through the anchor regions **25** and **26** of FIG. **4***c*. A beam polysilicon layer **12** is deposited next, followed by an implant, patterning and etching to define beams **14** and remove beam polysilicon layer **12** in the region between beam polysilicon layer **12** and beam **14** as shown in FIG. **4***d*. The thickness of beam polysilicon layer **12** is targeted at nominally 1.0 micrometer. A nominally 7500 angstrom LTO layer **32** is deposited conformally over microbeam **14** in FIG. **4***e*. The LTO is patterned with the upper cavity layer and etched to form cavity region **17** around the microbeam **14**. A thicker shell polysilicon layer **11** (at 1.0 to 4.0 micrometers) is deposited and implanted in FIG. **4***f*, followed by an intermediate temperature anneal to set the strain field and drive the implant. Shell polysilicon layer **11** and beam polysilicon layer **12** are then patterned and etched using the shell layer to form diaphragm **13**. A sacrificial etch is applied to remove LTO **27** and **32** thereby resulting in cavities **16** and **17**, as shown in FIG. **4***g*. Sacrificial etching **34** is done using 1:1 HF:HCl, followed by withdrawal and the latest sublimation techniques. A thin layer of LTO is deposited followed by a 1600 angstrom layer of polysilicon to seal in a vacuum and form the reactive seal. Alternatively, silicon nitride may be used for sealing, or a polysilicon seal with the oxide omitted. A nominally 1000 angstrom thick passivation layer **33** of silicon nitride is deposited, to enhance the seal and performing an additional function as an antireflection coating.

Stress isolation can be added by forming paddles upon which the absolute pressure sensor is located. A layer of LTO is deposited, patterned and etched with the trench layer, followed by etching of the silicon nitride layer and silicon through the epitaxial layer. An additional layer of LTO is deposited for sidewall passivation during anisotropic etching. The LTO is blanket etched from the top side, leaving oxide on the exposed sides of the n-epitaxial layer. After anisotropic etching in EDP, the LTO passivation layers are removed.

Optical methods may be used to drive and sense the oscillations of a resonant microbeam **14** using an optical fiber **36**. FIG. **5** shows an optically driven/sensed thin film resonant absolute pressure sensor. Light **35** from optical fiber **36** is trained on resonator **14**. A portion of light **35** is transmitted through shell layer **11** and the beam **14** layer, striking an underlying photodiode **37**. Light **35** generates an electric field, forcing microbeam **14** downward. Modulation of incident light **35** at the resonant frequency excites beam **14**, and results in a reflection of light **35** back through fiber **36** which is also modulated and sensed externally with a photodiode. A second method of excitation uses the self-resonant approach and operates with continuous wave incident light **35**.

Electrical drive/sense methods may be used to electrostatically excite the microbeam and piezoresistively sense the deflections. FIG. **6** shows an electrostatic drive line **38** and sensing piezoresistors with leadouts **40** for external electrical interconnection. Although single resonators **14** can be used to extract pressure readings, larger signals and a reduction in temperature sensitivity can be obtained using multiple resonators in a push-pull configuration. Cantilevered microbeam temperature sensors can be for temperature compensation. FIGS. **7***a* and **7***b*, and **8***a* and **8***b* show single and multiple resonator configurations, respectively. A single resonator **14** on a circular diaphragm **42** is shown schematically in FIG. **7***a* and on a square diaphragm **43** in FIG. **7***b*. Multiple resonators **14**, **41** and **44** on a circular diaphragm **42** are shown schematically in FIG. **8***a* and on a square diaphragm FIG. **8***b*.

Coupling to thin film resonators **14** using optical methods, for example, can induce undesirable packaging and mounting stresses on sensor **10**, causing baseline shifts and hysteresis. A method for achieving stress isolation is to mount sensing devices **10** on a suspended paddle **45** of a substrate **28**, in a side view of FIG. **9***a*, which appreciably reduces the effects of detrimental stresses. Sensor **10** is formed on substrate **28** prior to formation of paddle **45**.

FIG. **9***b* shows top view of stress isolated resonant microbeam absolute pressure sensor **10** on paddle **45** of substrate **28**. The stress isolation results from positioning device **10** on a single crystal silicon paddle **45**, suspended away from the mounting surfaces. Circular or square diaphragms can be mounted on paddle **45**. A trench **52** parts three sides of paddle **45** from die **28**. A square die **28** is illustrated, though it can also be circular.

A packaging configuration using an optical fiber **36** mounted to a silicon pressure sensor **10** die **46** is illustrated in FIGS. **10***a*, **10***b* and **10***c*. An optical fiber **36** is threaded through a glass or ceramic ferrule **47**, which may have funnels on one or both ends. Ferrule **47** is attached to silicon die **46** which may be either square or round. A round die may be formed by using through-the-wafer etching techniques. A cladding **48** surrounds optical fiber **36**. Optical fiber **36** is used to drive and sense microbeam **14**. Interface **49** provides for strain relief. A pressure port is cut into glass ferrule **47** or silicon die **46**. Other sensor functions (temperature, strain, magnetic field, and so forth) can be measured using this packaging approach with alternate configurations.

A resonant microbeam absolute pressure sensor **10** may be situated on a circular die **50**. Side and top views of this configuration are shown in FIGS. **11***a* and **11***b*, respectively. Resonant pressure sensor **10** is built in a recess **51**, to allow connection to a flat-faced ferrule **47** or cleaved fiber **36**. Sensor **10** is on paddle **45** that is suspended apart from die **50** by trench **52**. Dimensions **53** and **54** may be from 0.25 to 0.5 millimeter and from 0.5 to 2.5 millimeters, respectively.

We claim:

1. A resonant microbeam sensor comprising:

a substrate;

a first layer, having a microbeam and anchor supports, situated on said substrate such that there is a first cavity between said first layer and said substrate;

a second layer, situated on said first layer, forms a second cavity between said second and first layers, and first and second layers are annealed and integrated together to form a diaphragm; and

a p-n junction situated in said substrate and proximate to the microbeam for driving the microbeam into vibration and for sensing the vibration of the microbeam; and

wherein:

the diaphragm is deformable by external pressure impinging on the diaphragm;

deformation of the diaphragm charges stress and strain of the microbeam;

the resonant frequency of the microbeam varies with charges of the stress and strain of the microbeam;

the resonant frequency of the microbeam is a direct measure of the external pressure; and

the first layer of the diaphragm has a plurality of microbeams.

2. The sensor of claim **1** wherein the plurality of microbeams can function in a push-pull operation for temperature cancellation or compensation.

3. The sensor of claim **2** wherein:

said substrate comprises silicon; and

the diaphragm comprises polysilicon.

4. The sensor of claim **3** wherein the resonant microbeam sensor is formed on a cantilevered paddle that is an integral part of said substrate.

5. The sensor of claim **4** further comprising a passivation layer formed on the diaphragm and a peripheral portion of the substrate to aid in sealing the sensor and to provide antireflecting properties on the diaphragm.

6. A resonant microbeam sensor comprising:

a substrate;

a first layer, having a microbeam and anchor supports, situated on said substrate such that there is a first cavity between said first layer and said substrate;

a second layer, situated on said first layer, forms a second cavity between said second and first layers, and first and second layers are annealed and integrated together to form a diaphragm;

a p-n junction situated in said substrate and proximate to the microbeam for driving the microbeam into vibration and for sensing the vibration of the microbeam; and

an optical fiber proximate to the diaphragm for providing light to and receiving light reflected out of the diaphragm; and

wherein:

the microbeam has a resonant frequency which varies upon deformation of the diaphragm;

a near vacuum is within the first and second cavities;

light can be transmitted through the diaphragm and the microbeam onto the p-n junction, thereby can cause the microbeam to vibrate at its resonant frequency, and the light can be reflected out of the diaphragm from which the resonant frequency of the microbeam can be determined;

the optical fiber is threaded through a ferrule;

the microbeam sensor is situated in a die; and

the die is attached to the ferrule such that the diaphragm is proximate to an end of the optical fiber.

7. A resonant microbeam sensor comprising:

a substrate;

a first layer, having a microbeam and anchor supports, situated on said substrate such that there is a first cavity between said first layer and said substrate;

a second layer, situated on said first layer, forms a second cavity between said second and first layers, and first and second layers are annealed and integrated together to form a diaphragm; and

a p-n junction situated in said substrate and proximate to the microbeam for driving the microbeam into vibration and for sensing the vibration of the microbeam; and

wherein:

the diaphragm is deformable by external pressure impinging on the diaphragm;

deformation of the diaphragm charges stress and strain of the microbeam;

the resonant frequency of the microbeam varies with charges of the stress and strain of the microbeam;

the resonant frequency of the microbeam is a direct measure of the external pressure; and

the resonant microbeam is formed by two approximately parallel slits in the first layer.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,808,210

DATED : September 15, 1998

INVENTOR(S) : William R. Herb, David W. Burns

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1, line 5,

The Government may have certain rights in this invention pursuant to Contract No. DAAL01-94-C-3427, awarded by the Department of the Army.--

Signed and Sealed this

Fifth Day of January, 1999

Attest:

Attesting Officer

Acting Commissioner of Patents and Trademarks